Precise prediction for Higgs production via gluon fusion through many heavy quarks

Elisabetta Furlan

ETH Zürich

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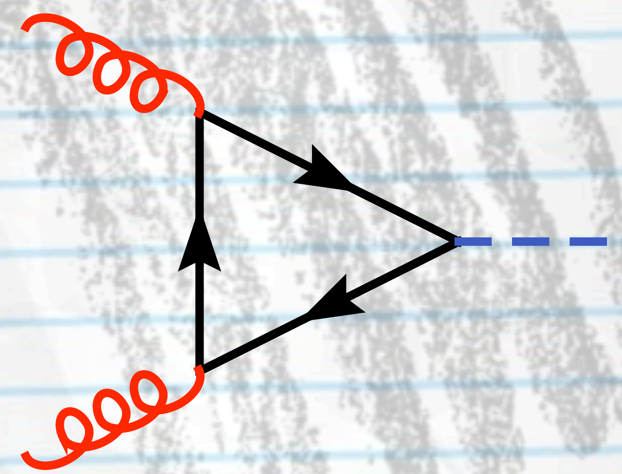
Motivation



* gluon fusion is the main mechanism for Higgs production at hadron colliders
* it is sensitive to any coloured particle that couples to the Higgs, e.g. the top
* the Higgs sector is untested
* the Standard Model Higgs sector is likely to be wrong
* extensions of the SM require new particles which may contribute to gluon fusion

this channel is very sensitive to new physics effects

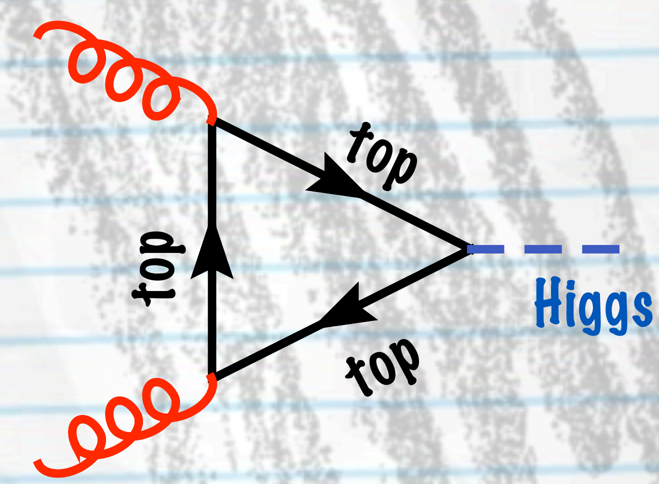
Motivation

* Assume that we find...
  - a relatively light Higgs with a cross section much different than σ_{SM} ($\sigma \sim 0.35\,\sigma_{SM}$, $\sigma \sim 0.80\,\sigma_{SM}$?)
  - and/or some new heavy particles

➡ lot of model-building activity ...

➡ ... and of perturbative QCD calculations of the gluon fusion cross section for these models

Gluon fusion in the SM



* it is known very precisely...
* ... but it required tough calculations

$$\sigma^{(SM)}_{NNLO} = \sigma^{(SM)}_{LO}\,(1 + \underbrace{0.7}_{\text{NLO}} + \underbrace{0.3}_{\text{NNLO}})$$

Harlander, Kilgore;
Anastasiou, Melnikov;
Ravindran, Smith, van Neerven

$$\left(\frac{\Delta\sigma}{\sigma}\right)^{\exp} \sim \pm 10\% \qquad , \qquad \left(\frac{\Delta\sigma}{\sigma}\right)^{NNLO}_{SM} \sim \pm 10\%$$

* ... and integrating out the top quark (HQET)

(Chetyrkin, Kniehl, Steinhauser)

Gluon fusion in BSM

* Only very recent NNLO calculations in some BSM scenarios
  - ➡ scalar octects (Boughezal, Petriello)
  - ➡ fourth generation (Anastasoiu, Boughezal, Furlan)
* Why?

  The low-energy theory is usually the same as in SM HQET, but the matching calculation at NNLO is much more complicated:

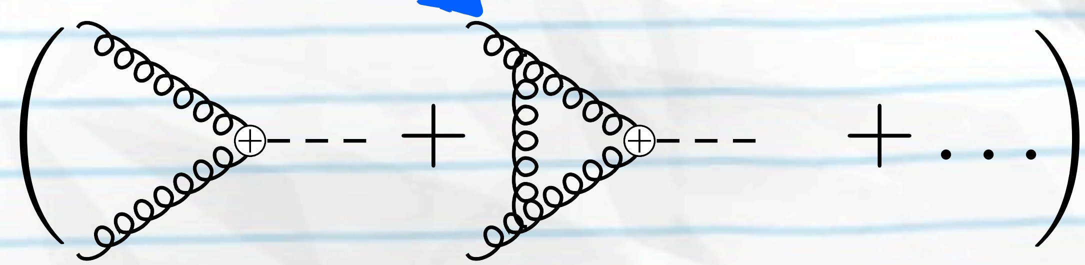
  * number of diagrams
  * renormalization
  * dependence on multiple mass scales

Separating new physics

* experiments (LEP, Tevatron, ..) indicate that new particles must be heavy, while the Higgs is light
* this allows for an effective-theory approach:

$$\mathcal{L}_{eff} = -\frac{\alpha_s}{4v} C \, H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\underbrace{\left(C_0 + \left(\frac{\alpha_s}{\pi}\right) C_1 + \left(\frac{\alpha_s}{\pi}\right)^2 C_2 + \dots \right)}_{\text{depends on the specific model}}$$

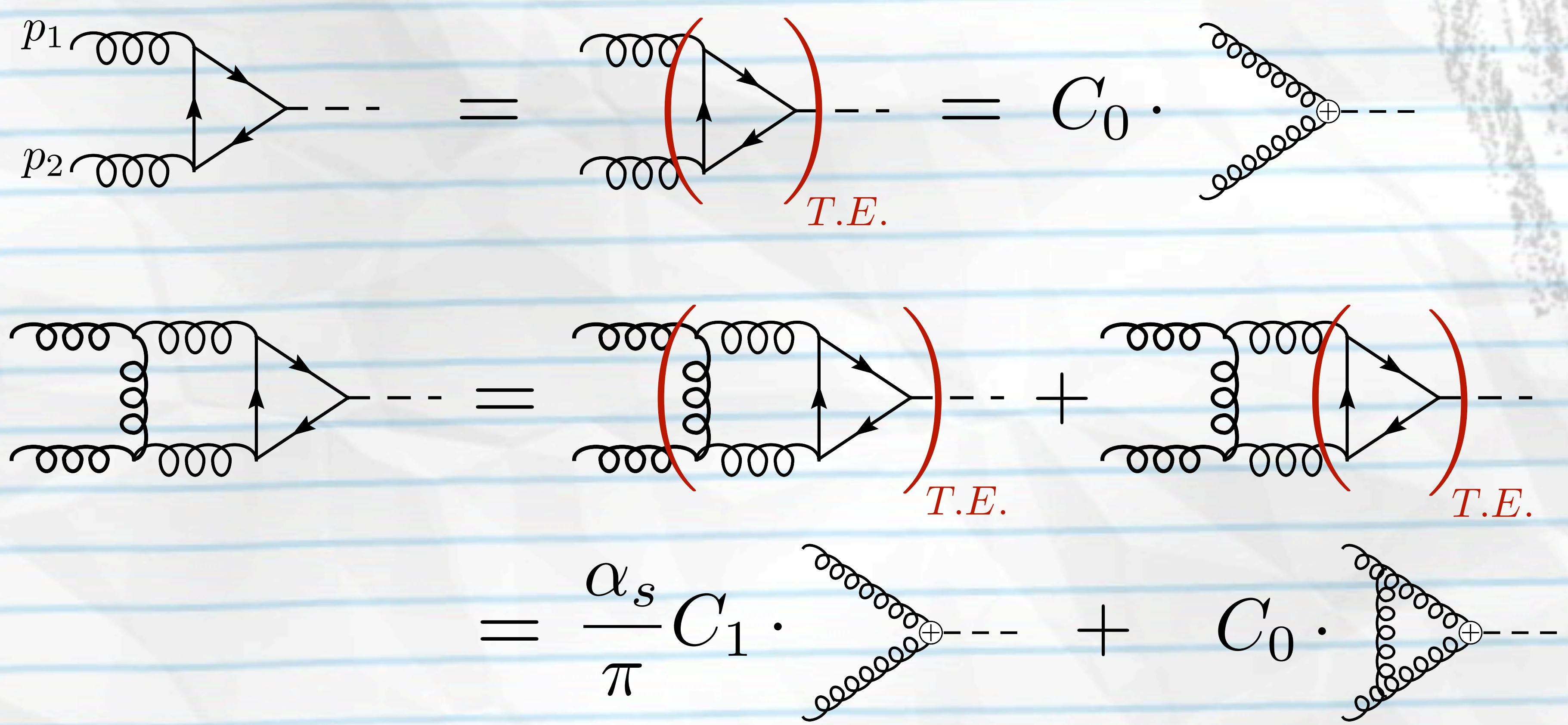


QCD only!

→ factorization of QCD and NP effects

Method

expansion by subgraphs (Chetyrkin; Gorishny; V. A. Smirnov)
+ small momentum expansion (Fleischer, Tarasov):



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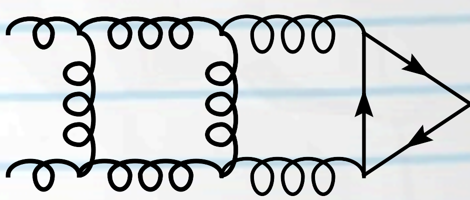
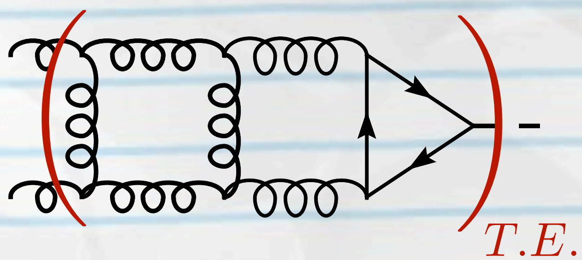
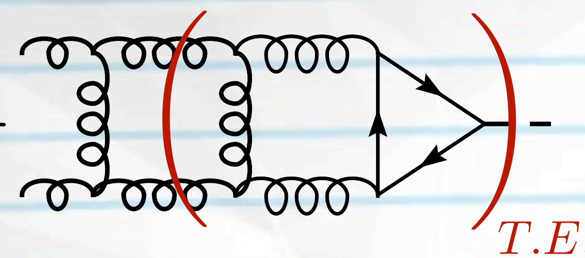
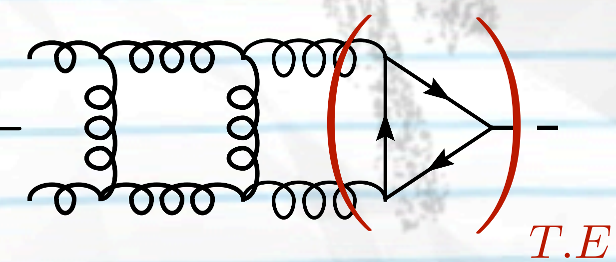
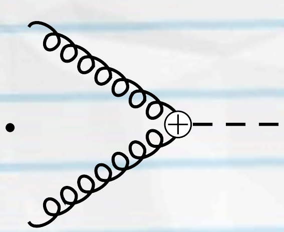
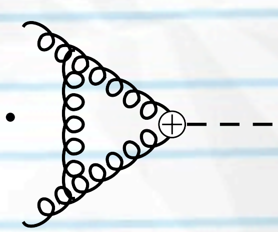
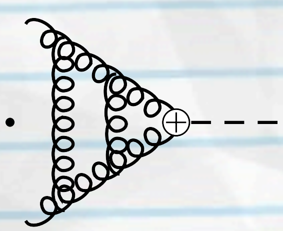
 $=$

 $+$  $+$ 

$= \left(\frac{\alpha_s}{\pi}\right)^2 C_2 \cdot$  $+ \frac{\alpha_s}{\pi} C_1 \cdot$  $+ \; C_0 \cdot$ 

Technical challenges

- Large number of Feynman diagrams
  $\sim$500 in the SM, $\sim$4000 in MSSM, $\sim$6000 in composite Higgs, ...
- Apply costly differentiations for Taylor expansion
- Reduce a large number ($\sim 10^5$) of integrals to master integrals

➡ we wrote our own routines in
  - ✦ QGRAF (Nogueira)
  - ✦ Mathematica
  - ✦ FORM (Vermaseren)
  - ✦ AIR (Anastasiou, Lazopoulos)

➡ same methods for SM and BSM Wilson coefficients

Technical challenges

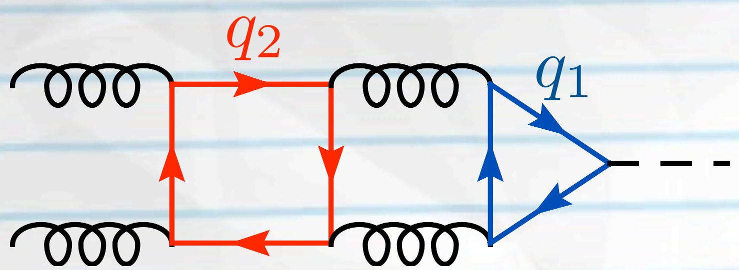
* Evaluate the master integrals
  ➡ much more difficult than in the SM (many mass scales)
  ➡ in many cases, impossible with traditional analytic methods -> sector decomposition

Hepp; Denner, Roth; Binoth, Heinrich; Anastasiou, Melnikov, Petriello; Anastasiou, Beerli, Daleo; Lazopoulos, Melnikov, Petriello

Many heavy quarks!

in collaboration with C. Anastasiou and R. Boughezal

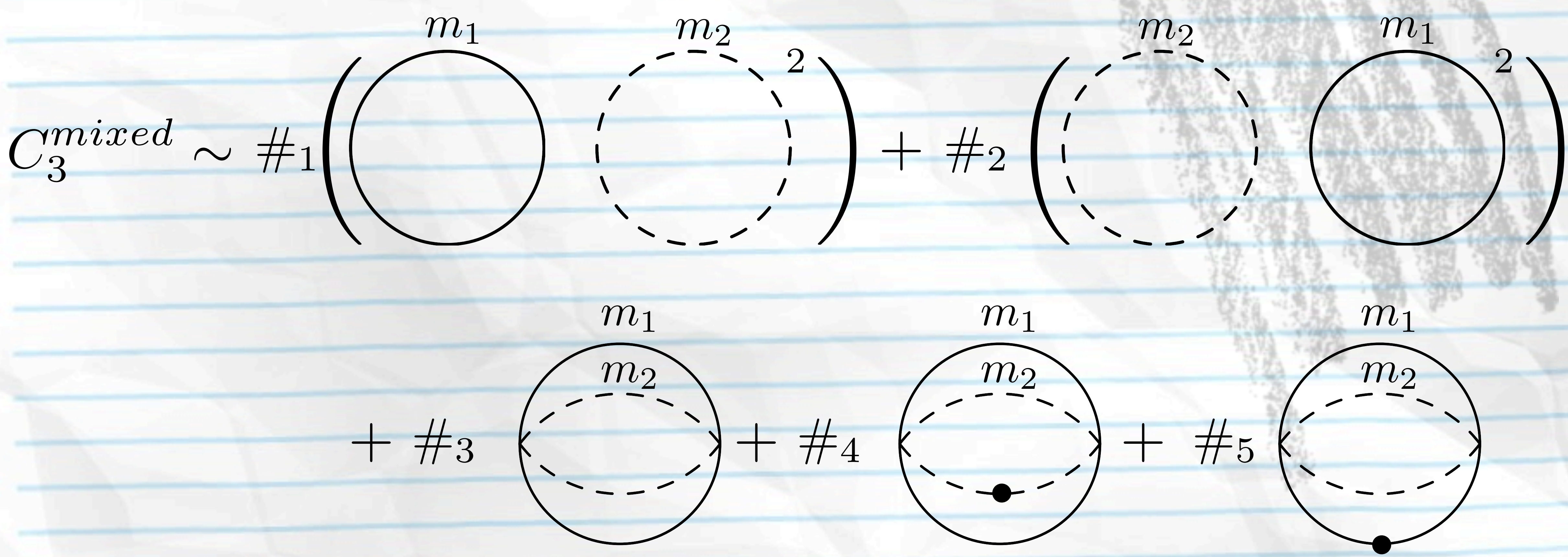
* the two mass scales appear together at NNLO for the first time:



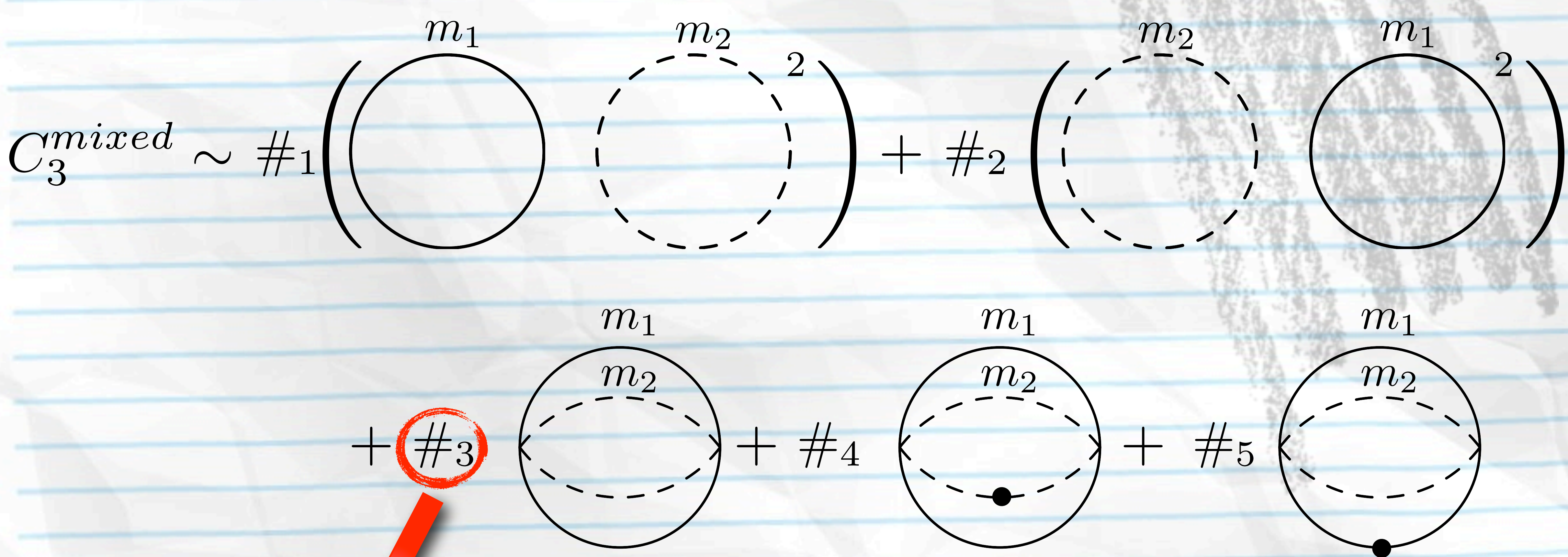
+ other 115

- can use the same routines as for the SM calculation
- master integrals now contain up to two, different, massive propagators

Many heavy quarks!

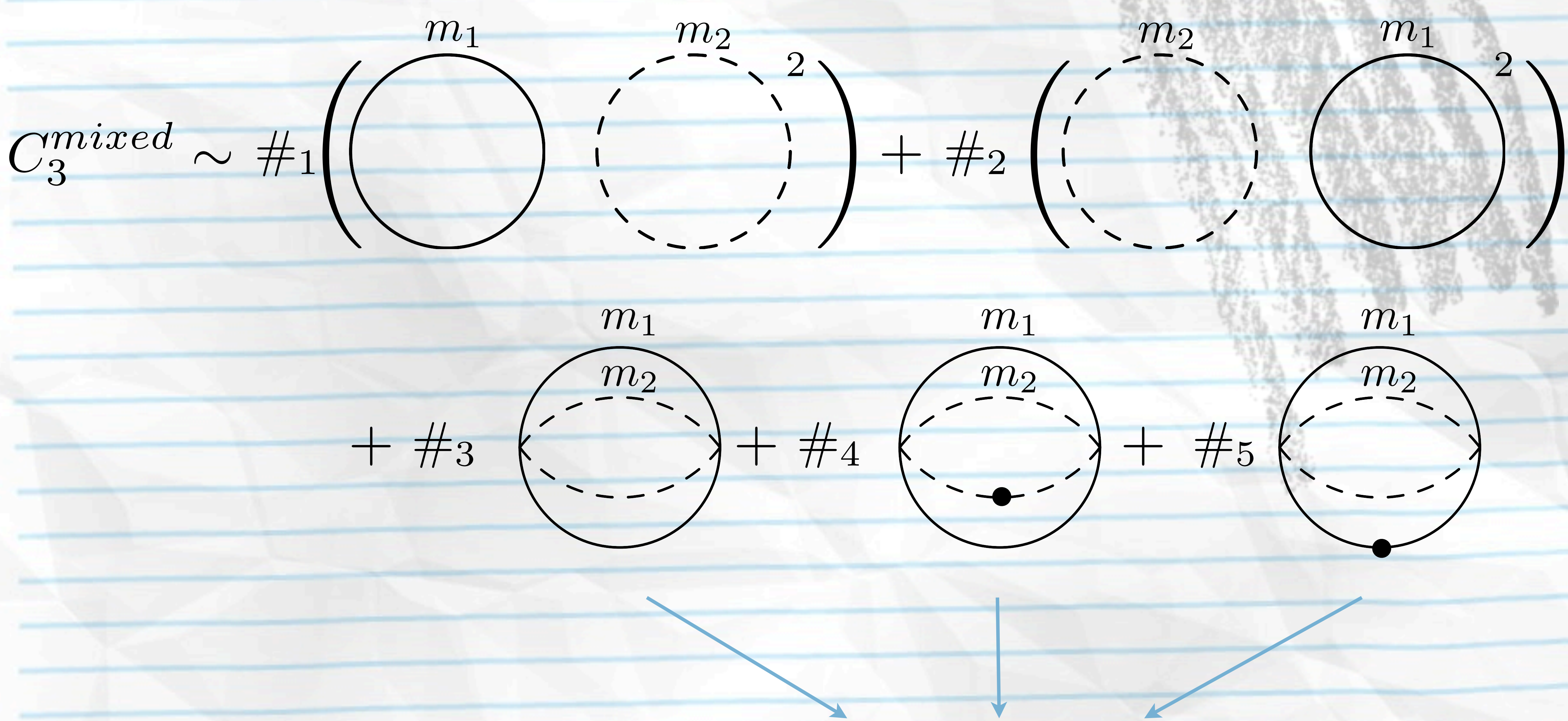


Many heavy quarks!



$$\frac{\alpha_s^3}{2m_1^4 m_2^6}\left[\frac{(19m_1^6+5m_1^4m_2^2-5m_1^2m_2^4-19m_2^6)}{\epsilon} - \frac{1713m_1^8+476m_1^6m_2^2-1834m_1^4m_2^4-964m_1^2m_2^6-1023m_2^8}{36(m_1^2-m_2^2)}\right]$$

Many heavy quarks!



Bekavac, Grozin, Seidel, Smirnov

Many heavy quarks!

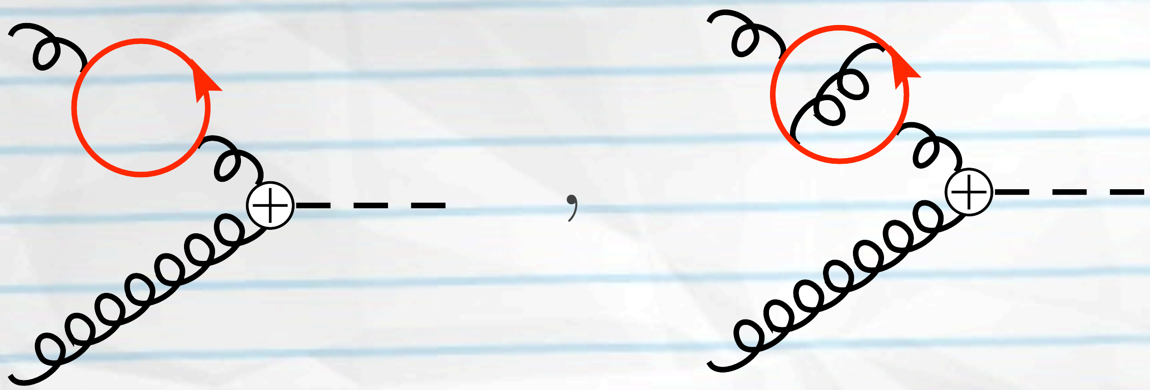
* Contribution to the bare NNLO Wilson coefficient from two-quarks diagrams:

$$
\begin{aligned}
-\left(\frac{\alpha_s^0 S_\epsilon}{\pi}\right)^3 \Bigg\{ & \frac{1}{16\epsilon^2} - \frac{1}{16\epsilon}\left[3\left(\log(m_1^0)+\log(m_2^0)\right)+\frac{89}{18}\right] \\
& + \frac{1}{2}\log(m_1^0)\log(m_2^0) + \frac{89}{96}\left[\log(m_1^0)+\log(m_2^0)\right] \\
& + \frac{5}{16}\left[\log^2(m_1^0)+\log^2(m_2^0)\right] + \frac{1051+27\pi^2}{1728} + \mathcal{O}(\epsilon) \Bigg\}
\end{aligned}
$$

$$
S_\epsilon = e^{-\epsilon\gamma_E}\,(4\pi)^\epsilon
$$

Next steps...

* Decoupling of the heavy quarks:
  - ➡ heavy quarks give loop contributions to the self-energies and vertices



  - ➡ absorb these contributions into decoupling constants
    (Chetyrkin, Kniehl, Steinhauser)
* Renormalization

RESULT

* NNLO Wilson coefficient for an arbitrary number n_h of heavy quarks:

$$\mathbf{C} = -\frac{1}{3}\frac{\alpha_s'(\mu)}{\pi}\left\{ n_h + \frac{11}{4}\frac{\alpha_s'(\mu)}{\pi} n_h - \left(\frac{\alpha_s'(\mu)}{\pi}\right)^2 \left[\frac{77}{576} n_h^2 - \frac{1877}{192} n_h + \frac{19 L_m}{8} + n_l \left(\frac{67}{96} n_h + \frac{2 L_m}{3}\right)\right]\right\}$$

$$L_m = \sum_{q=1}^{n_h} \log\left(\frac{m_q(\mu)}{\mu}\right)$$

Application: 4th generation

* our result allows to put reliable experimental bounds on the Higgs boson mass in this model

* we include:

  ➡ the exact LO and NLO amplitude for the heavy quarks and for the bottom quark

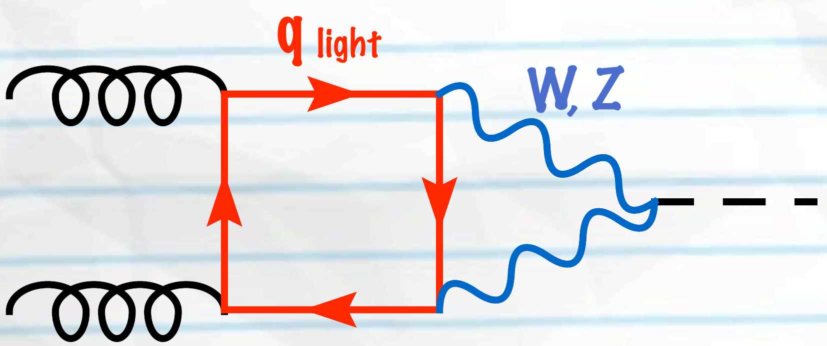
  (Wilczek; Ellis et al.; Georgi et al.)

  (Spira et al.; Anastasiou et al.)

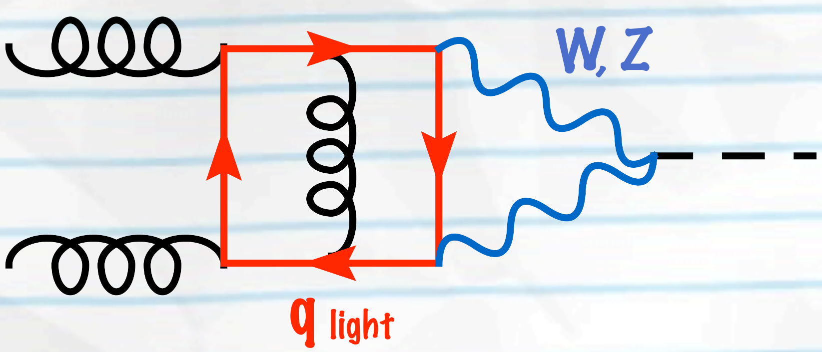
  ➡ our NNLO Wilson coefficient in the heavy-quark approximation

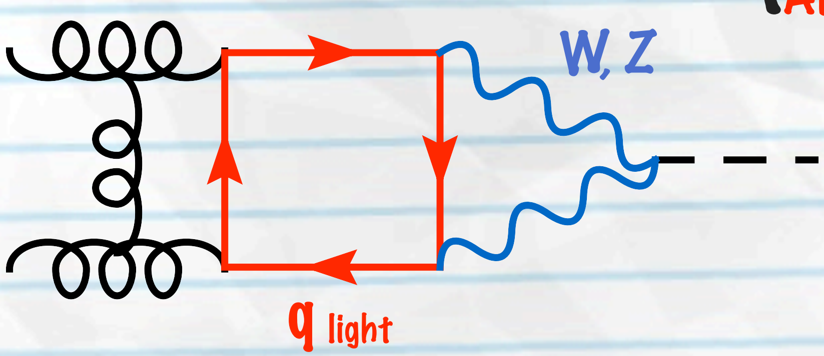
Higgs production cross-section

➡ the two-loop electroweak corrections: (Aglietti et al.)



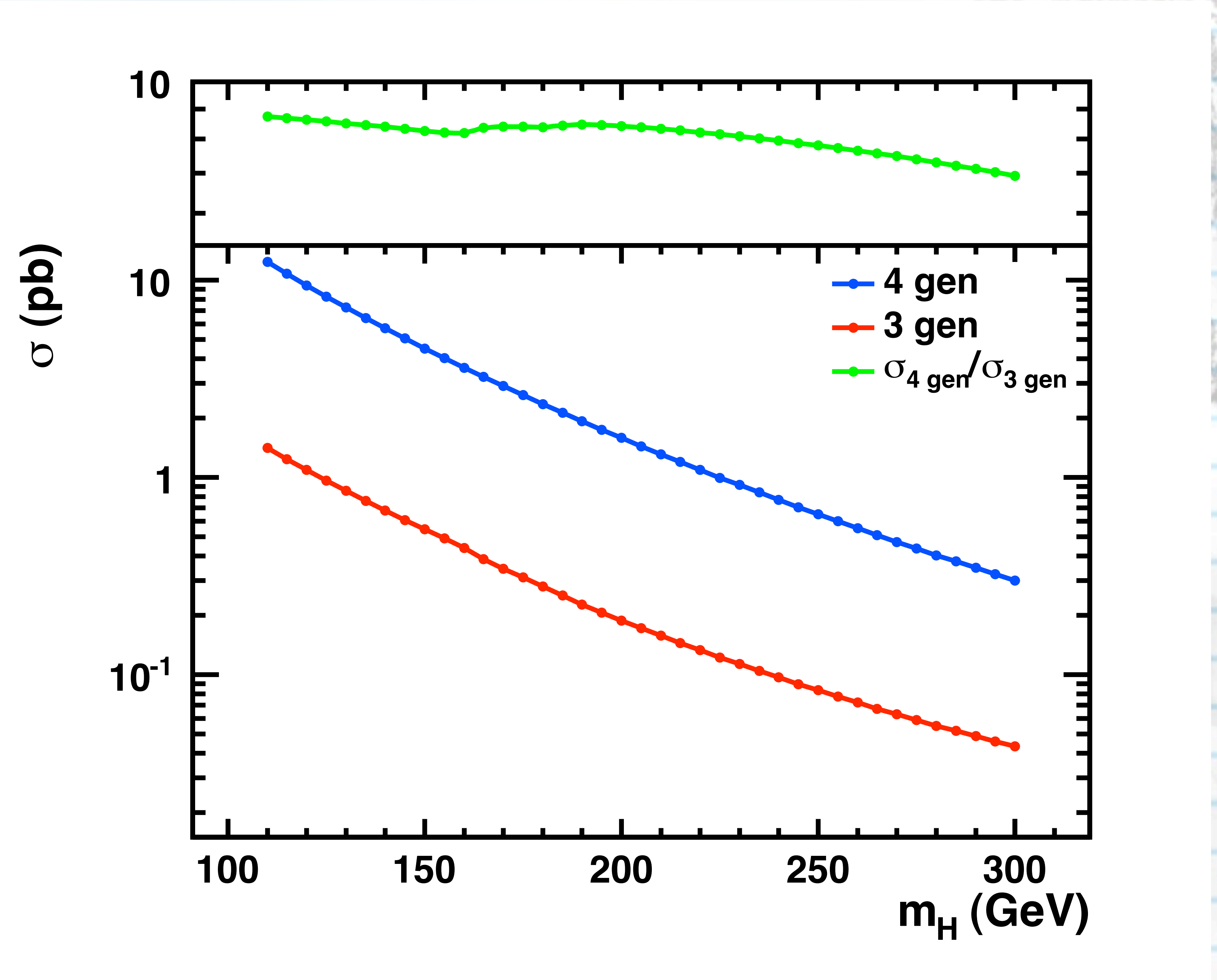
➡ the three-loop mixed QCD-electroweak corrections: (Anastasiou et al.)





and the total cross-section is..

Higgs production cross-section



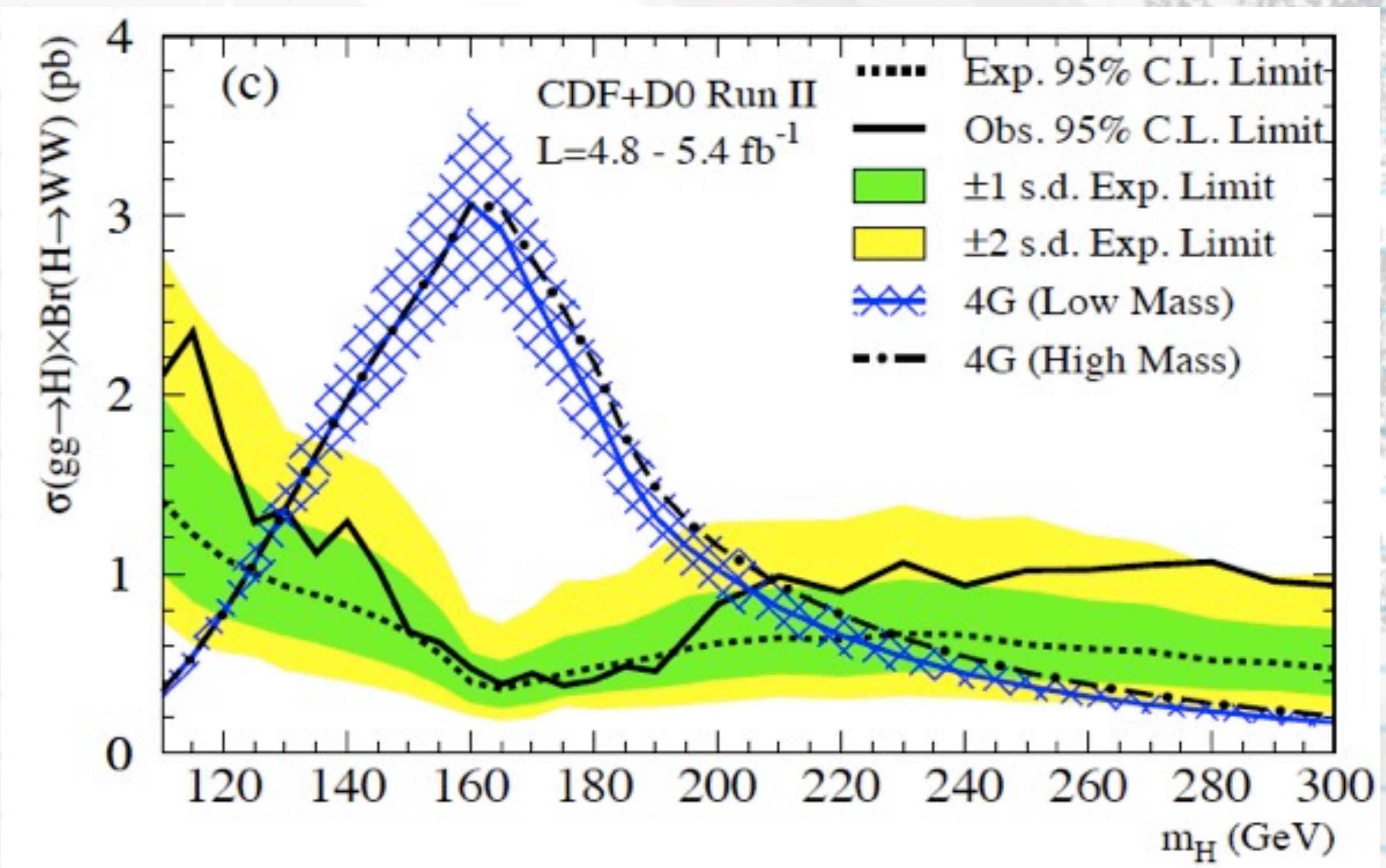
$m_B = 400$ GeV , $m_T \simeq m_B + 50$ GeV $+ 10$ GeV $\mathrm{Log}(m_H/115$ GeV$)$

Higgs production cross-section

- ➡ the NNLO cross section is 20-30% higher than the NLO cross-section
- ➡ the enhancement over the SM production cross section varies between 9 and 7, depending on m_H
- ➡ the theory uncertainty on the NLO cross-section is much higher than the experimental uncertainty

* this result allows to put accurate constraints on the mass of the Higgs boson in the four-generation SM

Exclusion limits on m_H



(CDF & D0)

➡ exclude $131\ \text{GeV} \lesssim m_H \lesssim 204\ \text{GeV}$

Conclusions

* the Higgs boson is likely to come with some new physics
* many viable BSM theories exist, and many need to introduce new, coloured particles
* they can significantly affect the gluon-fusion cross section
* effective theory disentangles new physics from QCD
* we have automatised the matching procedure for BSM models through NNLO

Conclusions

* ready for high-precision predictions for Higgs boson cross-section in extensions of the SM
* first application: Higgs production cross-section in the four-generation SM
* this result can be combined with experimental results to put reliable bounds on the Higgs boson mass in the four-generation model